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14. ABSTRACT
We have performed a set of experiments using arrays of 1D Bose gases in various configurations. Uncoupled 1D gases have been used to study the limits of statistical mechanics near integrable points. We have shown that nearly integrable gases thermalize at an even slower rate than quantum statistical mechanics predicts, evidence of a long sought quantum KAM regime. With coupled tubes, we studied how correlations inhibit tunneling. With uncoupled tubes plus an axial lattice we have studied non-equilibrium dynamics after a quantum quench. The basic dynamics,

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Report Title

Final Report: Quantum Computation with Neutral Atoms at Addressable Optical Lattice Sites and Atoms in Confined Geometries

ABSTRACT

We have performed a set of experiments using arrays of 1D Bose gases in various configurations. Uncoupled 1D gases have been used to study the limits of statistical mechanics near integrable points. We have shown that nearly integrable gases thermalize at an even slower rate than quantum statistical mechanics predicts, evidence of a long sought quantum KAM regime. With coupled tubes, we studied how correlations inhibit tunneling. With uncoupled tubes plus an axial lattice we have studied non-equilibrium dynamics after a quantum quench. The basic dynamics, which include doublon dissolution, quantum distillation, and confinement of vacancies in a doublon sea, can be qualitatively understood even in the intermediate coupling limit where exact theoretical calculations are difficult. We also worked, in a separate apparatus, on the development of a neutral atom quantum computer. We have recently gotten to the point of being able to execute arbitrary single qubit gates on any site in a 5x5x5 array.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
10/09/2014	2.00	Xiao Li, Karl D. Nelson, David S. Weiss. Imaging single atoms in a three-dimensional array, Nature Physics, (06 2007): 556. doi: 10.1038/nphys645
10/09/2014	3.00	Vladimir A. Yurovsky, Maxim Olshanii, David S. Weiss. COLLISIONS, CORRELATIONS, ANDINTEGRABILITY IN ATOM WAVEGUIDES, Advances in Atomic, Molecular and Optical Physics, (06 2008): 61. doi:
10/09/2014	4.00	Birjoo Vaishnav, David S. Weiss. Site-resolved Bragg scattering, Optics Letters, (02 2008): 375. doi:
10/09/2014	5.00	Xiao Li, Theodore A. Corcovilos, Yang Wang, David S. Weiss. 3D Projection Sideband Cooling, Physical Review Letters, (03 2012): 103001. doi: 10.1103/PhysRevLett.108.103001
10/09/2014	6.00	Jean-Félix Riou, Aaron Reinhard, Laura A. Zundel, David S. Weiss. Spontaneous-emission-induced transition rates between atomic states in optical lattices, Physical Review A, (09 2012): 0. doi: 10.1103/PhysRevA.86.033412
10/09/2014	7.00	Aaron Reinhard, Jean-Félix Riou, Laura Zundel, David Weiss, Shuming Li, Ana Rey, Rafael Hipolito. Self-Trapping in an Array of Coupled 1D Bose Gases, Physical Review Letters, (01 2013): 33001. doi: 10.1103/PhysRevLett.110.033001
10/09/2014	10.00	Jean-Félix Riou, Laura A. Zundel, Aaron Reinhard, David S. Weiss. Effect of optical-lattice heating on the momentum distribution of a one-dimensional Bose gas, Physical Review A, (09 2014): 33401. doi: 10.1103/PhysRevA.90.033401
10/09/2014	8.00	Shuming Li, Salvatore R. Manmana, Ana Maria Rey, Rafael Hipolito, Aaron Reinhard, Jean-Félix Riou, Laura A. Zundel, David S. Weiss. Self-trapping dynamics in a two-dimensional optical lattice, Physical Review A, (08 2013): 23419. doi: 10.1103/PhysRevA.88.023419
10/09/2014	9.00	Aaron Reinhard, Jean-Félix Riou, Laura A. Zundel, David S. Weiss. Dark-ground imaging of high optical thickness atom clouds, Optics Communications, (08 2014): 30. doi: 10.1016/j.optcom.2014.02.070

TOTAL: **9**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 37.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Penn State Faculty Scholars Medal, 2007
APS Fellow, 2007-
elected vice Chair of DAMOP, 2013

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Xiao Li	0.23	
Laura Zundel	0.07	
FTE Equivalent:	**0.30**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Karl Nelson	0.18
Jean-Felix Riou	0.01
Aaron Reinhard	0.01
Lin Xia	0.13
FTE Equivalent:	**0.33**
Total Number:	**4**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
David Weiss	0.05	
FTE Equivalent:	**0.05**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Xiao Li	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Work proceeded on two experimental apparatuses. In our apparatus to study quantum gases in reduced dimensions, we have worked on several distinct lines of experimentation.

Thermalization: Our study of thermalization in 1D Bose gases extended over the life of this grant. Before this grant period we had demonstrated the quantum Newton's cradle (QNC). We observed that when 1D Bose gases are taken far from equilibrium, they approximate integrable systems well enough that they did not thermalize even after thousands of two body collisions. This raised the question, what is the minimum that needs to be done for an isolated system to thermalize, by which we mean come to a long term steady state that does not depend on details of the initial state. The border between integrable systems and ergodic systems is well understood in classical mechanics (with the so-called KAM theorem), but it is poorly understood in quantum mechanics.

To access a possible quantum KAM regime we increased the density in the QNC and decreased the heating by various technical measures. We then studied in great detail all the processes that cause the momentum distribution to evolve, in order to isolate the effect of the onset of thermalization. This led us study exactly how spontaneous emission deposits energy in a 2D lattice, and then to develop a Monte Carlo simulation of how that energy (and energy from a host of other smaller energy deposition processes) propagates through the gas. At low density, our Monte Carlo matches the evolution of momentum distributions in great detail. The idea was then to see if there was any evolution at high density that could not be explained by the heating model.

The most obvious density dependent effect on 1D gas evolution is 3-body inelastic loss, which we therefore also had to study in detail. We wanted to use the inelastic loss to calibrate the rate of elastic 3-body collisions that could lead to thermalization. The rate of these "diffractive"3-body collisions, which result from unavoidable non-integrability in real waveguides, has been calculated. However, the three-body correlations of the out-of-equilbirum gas has not been calculated, so the inelastic collisions were a critical input for determining how fast thermalization should proceed. Our observable for the onset of thermalization is evaporative cooling, which can be a very sensitive indicator. Energy changes due to inelastic 3-body loss, however, might have obscured this signal, especially since one would naively think that loss would tend to heat, since the densest region of the gas has colder particles. Remarkably, we found that the changes in the correlations are such that more energetic particles are disproportionately likely participate in three-body collisions. By studying QNCs of varying energies, we infer that 3-body loss has a very small effect on the shape of momentum distributions (manuscript in preparation). Any disagreement between our Monte Carlo evolution at high density and our observations are thus solely due to diffractive 3-body collisions.

The punchline is that there is almost no disagreement, even though the parameters are such that we should be more than halfway to thermalized. This is the first indication that conventional statistical mechanics fails in the slightly non-integrable regime (manuscript in preparation). Apart from its significance for our basic understanding of quantum statistical mechanics, where thermalization has been just an assumption, these experiments directly address the practical issue of whether one can count on atoms in an optical lattice simulation to thermalize, as long as the Hamiltonian is not integrable. The short answer is that it cannot be taken for granted.

Correlation suppressed tunneling: We performed experiments with an array of coupled 1D gases, and found that in the intermediate coupling limit, there is no fix to mean field theory that explains the suppression of tunneling among the tubes. This correlation-based suppression is still rather poorly understood theoretically.

Imaging high density distributions: We developed a technique for imaging high density distributions. It is simple and robust, and critical for the work described in the previous paragraph. But its applications are more of the boutique type.

Expansion in a flat 1D lattice: We embarked on experiments to study quantum quenches in 1D lattice gases during the grant period, although the bulk of the work proceeded after the grant ended. (The paper has been submitted.) We revived our ability to photoassociate atoms, and used that tool to separately study the spatial evolution of singlons, doublons and triplons in the gas. The evolution is quite rich, and includes: the dissolution of doublons, even with a deep enough lattice that isolated doublons are stable; the quantum distillation of singlons out of the doublon sea; and the long term confinement of some singlons, depending on their quasimomenta, in the doublons sea. We hope that this will contribute to the understanding of universal behavior in out-of-equilibrium quantum dynamics.

Quantum computing: In our apparatus designed for single atom addressability and quantum computation, we developed the ability to make very reliable occupancy maps of approximately half filled 5x5x5, 5 micron-spaced lattices, along with a complementary technique to measure the hyperfine states at each lattice site. We developed a technique to cool atoms so that they are mostly in the vibrational ground states of their respective lattice sites. We then set about addressing individual lattice sites. We accomplish this by directing orthogonal addressing beams, using fast microelectromechanical systems (MEMS) mirrors, at the atoms, and shifting only the target atom into resonance with microwaves that drive a gate. The lion share of the work has been in making the entire optical system stable to within ~100 nm, which includes the imaging system, the lattice positions, and the pair of addressing beams. The current state of the experiment is that we have demonstrated arbitrary single qubit gates at targeted sites, while leaving quantum information at untargeted sites untouched.

Technology Transfer